Implications on the mUED model from the early LHC data on $\ell + \not{E}_T$ signal.

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Abstract

Recently the ATLAS and CMS collaborations reported their search for a new heavy gauge boson W' with one lepton plus missing transverse momentum. We find that $W^{(2)}$, the second Kaluza-Kelin (KK) state of the W boson in the minimal Universal Extra Dimension (mUED) model, can be a good candidate for this signal, as its branching ratio into $\ell\nu$ is sizable. Moreover, nearly degenerate KK mass spectra in the mUED model yield generically very soft SM particle accompanying $W^{(2)}$ from the subsequent decays of the second KK quarks and gluons. In a hadron collider, this indirect $W^{(2)}$ production is difficult to distinguish from the $W^{(2)}$ single production. The involved strong interactions make it more important than the single production. The early LHC data on $\ell + \not{E}_T$ signal for 1.1 fb^{-1} integrated luminosity is shown insufficient to limit our model even with significant indirect production of $W^{(2)}$. However, the results show that the present LHC 5.6 fb^{-1} data can cover most of the reasonable parameter space of the mUED model.

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I. INTRODUCTION

The performance of the LHC in 2010 and 2011 has been captivatingly successful. Initial goal of integrated luminosity in 2011 was 1 fb^{-1}, but already 5.6 fb^{-1} data have been delivered, respectively, to the ATLAS and CMS detectors by the end of August in 2011 [1]. Even with partial and early data of the LHC, significant constraints have been made on many new physics models such as supersymmetry models [2], Z' models [3], and W' models [4].

One of the most sensitive and clean probe for new physics is the event with a highly energetic electron or muon and the large missing transverse energy $\not{E}_T$. The CMS [5] and ATLAS collaborations [6] have reported the analysis of $\ell + \not{E}_T$ data corresponding to an integrated luminosity of 36 pb^{-1}. Both experiments found no excess beyond the SM expectations. Using a reference W' model, in which a heavy W' has the same left-handed fermionic couplings and vanishing interactions with the SM gauge bosons, the lower bound on the W' mass has been made to be about 1.4 TeV. Recently it is far more refined to be 2.27 TeV with 1 fb^{-1} luminosity data collected in 2011 [7]. Recently their implications on various new physics models, such as non-universal gauge interaction model [8], minimal walking technicolor model [9], and left-right model [10], have been extensively studied.

We find that the Universal Extra Dimension (UED) model has a good candidate to mimic the W' decaying into $\ell\nu$, the second Kaluza-Klein (KK) mode of the W boson, $W^{(2)}$. In addition, the minimal version of the UED model, called the mUED model, has additional enhancement of the $W^{(2)}$ production at the LHC. The UED model is based on a single flat extra dimension of size R, compactified on an S_1/Z_2 orbifold. This fifth dimensional space is accessed by all the SM fields. Thus all the SM fields have an infinite number of KK excited states of which the zero modes are identified to the SM fields. At tree level the KK number n is conserved by the fifth dimensional momentum conservation, but broken to the KK parity at loop level. Due to the KK parity conservation, the lightest KK particle (LKP) with odd KK parity is stable and becomes a good candidate of the cold dark matter. In the mUED model, the boundary kinetic terms are assumed to vanish at the cut-off scale Λ. Radiative corrections to the KK masses are finite and calculable: the first KK mode of the $U(1)_Y$ gauge boson $B^{(1)}$ is the LKP [12]. The thermal relic density of $B^{(1)}$ with mass around 500 GeV can explain all of the dark matter [13]. In order to avoid over-closing the universe, the $B^{(1)}$ mass is constrained to be below about 600 GeV [14].

Various phenomenological study of the mUED has been done in the literature [15]. There are two distinctive features that differentiate the mUED model from other new physics models: the nearly degenerate KK mass spectra of new particles and the presence of heavy parity-even ($n = 2$) particles [16, 17]. These two features leave very interesting phenomenology associated with the second KK modes, especially $W^{(2)}$.

In this paper, we examine the production of the $W^{(2)}$ boson followed by its decay into $\ell\nu$ in the mUED model, and study the constraints by the early LHC data. Due to the kinematic suppression by nearly degenerate KK mass spectra, the KK-number conserving decays of $W^{(2)} \to f^{(2)}\bar{f}'^{(0)}$ and $W^{(2)} \to f^{(1)}\bar{f}'^{(1)}$ are not dominant. The KK-number violating decays into two SM fermions at one loop level are considerable. Moreover we notify that there are sizable indirect production of $W^{(2)}$ boson in the decays of heavier colored KK states of $n = 2$, *i.e.*, the second KK quarks $Q^{(2)}$ and gluons $g^{(2)}$. The SM particles, which are by-products of these cascade decays, are generically very soft due to the degenerate masses of the second KK states. Thus the transverse mass distribution of the leptons from indirectly produced $W^{(2)}$ is similar to that from singly produced $W^{(2)}$. This indirect production is more important than the direct production. This is our main result.

The paper is organized as follows. In the section II, we briefly describe the model and discuss the production and decay of the $W^{(2)}$ boson. Section III is devoted to the analysis with the data collected at the LHC and Tevatron. We conclude in Sec. IV.

II. PRODUCTIONS AND DECAYS OF $W^{(2)}$ BOSON IN THE MUED MODEL

The UED model is based on an additional extra dimension y with size R where all the SM fields propagate. The fifth dimension y is compactified on an S_1/Z_2 orbifold for generating zero mode chiral fermions. We assign odd parity under the Z_2 orbifold symmetry to the zero mode fermion with wrong chirality. This extends the fermion sector into $SU(2)$-doublet quark $Q(x, y)$ and $SU(2)$-singlet quark $q(x, y)|_{q=u,d}$. After compactification, we obtain four-dimensional effective Lagrangian with the zero modes and the KK excited states. Focused on the phenomenology of the second KK modes of W boson, we present the relevant KK expansions of

$$V_\mu(x, y) = \frac{1}{\sqrt{\pi R}} \left[V_\mu^{(0)}(x) + \sqrt{2} \sum_{n=1}^{\infty} V_\mu^{(n)}(x) \cos\frac{ny}{R} \right], \tag{1}$$

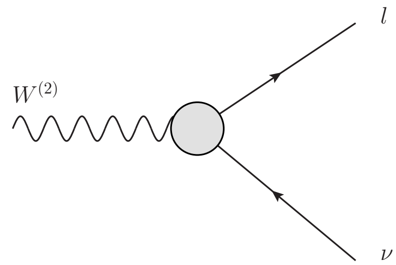

FIG. 1: Feynman diagrams for the decay of the $W^{(2)}$ boson.

$$V_5(x,y) = \sqrt{\frac{2}{\pi R}} \sum_{n=1}^{\infty} V_5^{(n)}(x) \sin \frac{ny}{R},$$

$$Q(x,y) = \frac{1}{\sqrt{\pi R}} \left[Q_L^{(0)}(x) + \sqrt{2} \sum_{n=1}^{\infty} \left\{ Q_L^{(n)}(x) \cos \frac{ny}{R} + Q_R^{(n)}(x) \sin \frac{ny}{R} \right\} \right],$$

$$q(x,y) = \frac{1}{\sqrt{\pi R}} \left[q_R^{(0)}(x) + \sqrt{2} \sum_{n=1}^{\infty} \left\{ q_R^{(n)}(x) \cos \frac{ny}{R} + q_L^{(n)}(x) \sin \frac{ny}{R} \right\} \right],$$

where $V^M = B^M, W^M, A^M, g^M$, and n is the KK number.

The n-th KK mass of a gauge boson V is given by

$$M_{V^{(n)}}^2 = M_n^2 + m_0^2 + \delta m_{V^{(n)}}^2, \tag{2}$$

where $M_n = n/R$, m_0 is the corresponding SM particle mass and $\delta m_{(n)}^2$ is the radiative corrections. There are two types of radiative corrections to the KK mass, which break generically five-dimensional Lorentz invariance. The first is the bulk correction from compactification or non-local loop-diagrams around the circle of the compactified dimension y. Since this propagation is over finite distances, these bulk corrections are well-defined and finite. The second type of radiative corrections are from the boundary kinetic terms, which are incalculable due to unknown physics at the cutoff scale Λ. The mUED model is based on the assumption that the boundary kinetic terms vanish at the cutoff scale Λ. The radiative correction to the KK mass of the $W^{(n)}$ bosons is given by [12]

$$\delta m_{W^{(n)}}^2 = -\frac{5}{2} \frac{g^2 \zeta(3)}{16\pi^4} \frac{1}{R^2} + M_n^2 \frac{15}{2} \frac{g^2}{16\pi^2} \ln \frac{\Lambda^2}{\mu^2}, \tag{3}$$

where the renormalization scale μ is normally set to be M_n.

Search for a charged heavy gauge boson W' at the LHC is being conducted in its leptonic decay channels with electron and muon final states: see Fig. 1. The relevant KK-number

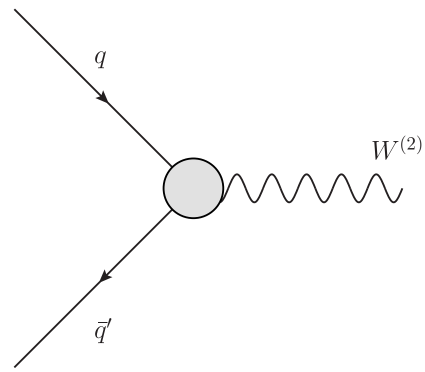

FIG. 2: Feynman diagrams for the single production of the $W^{(2)}$ boson.

violating operator is

$$\mathcal{L}_{200} = i\hat{g}_{ff'}\left(\frac{g}{2}\frac{1}{16\pi^2}\ln\frac{\Lambda^2}{\mu^2}\right)\bar{f}\gamma^\mu P_L f' W^{(2)}_\mu, \tag{4}$$

where

$$\hat{g}_{\ell\nu} = \frac{9}{8}g'^2 - \frac{33}{8}g^2, \quad \hat{g}_{qq'} = \frac{1}{8}g'^2 - \frac{33}{8}g^2 + 6g_s^2. \tag{5}$$

The branching ratios of $W^{(2)}$ have been computed in Ref. [18]. Depending on R^{-1}, $\mathrm{Br}(W^{(2)} \to l\nu) \sim 2-3\%$.

As depicted in Fig. 2, the single production of $W^{(2)}$ boson is through the KK-number violating operator $\mathcal{L}_{200}$ with $f = q$. The production cross section is $\sigma(pp \to W^{(2)}) \sim \mathcal{O}(0.1)\,\mathrm{pb}$ for $1/R = 500$ GeV [18].

At the LHC, the $W^{(2)}$ boson is also produced through the cascade decays of a heavier second KK modes, $Q^{(2)}$ and $g^{(2)}$. In the mUED model, the KK mass spectra are unambiguously fixed, leading to the hierarchy of $M_{g^{(2)}} > M_{Q^{(2)}} > m_{W^{(2)}}$. As shown in Fig. 3, the second KK gluon $g^{(2)}$ can decay into $Q^{(2)}q$ with branching ratio of about 50%, and $Q^{(2)}$ decays into $W^{(2)}q'$ with branching ratio of about 50%. Small mass differences of $M_{g^{(2)}} - M_{Q^{(2)}}$ and $M_{Q^{(2)}} - M_{W^{(2)}}$ make the accompanying SM quarks very soft. At a hadron collider, the phenomenological signature of the indirectly produced $W^{(2)}$ boson is likely to be indistinguishable from that of the singly produced $W^{(2)}$. As shall be shown, this indirect production of $W^{(2)}$ is more important.

Figure 3 illustrates the indirect production of $W^{(2)}$ accompanying soft jets. In Fig. 3(a), $g^{(2)}$ is singly produced, followed by its decay of $g^{(2)} \to Q^{(2)}q$ and $Q^{(2)} \to W^{(2)}q'$. Nearly degenerate mass spectrum yields very soft jets. Note that the single production of $Q^{(2)}$ is

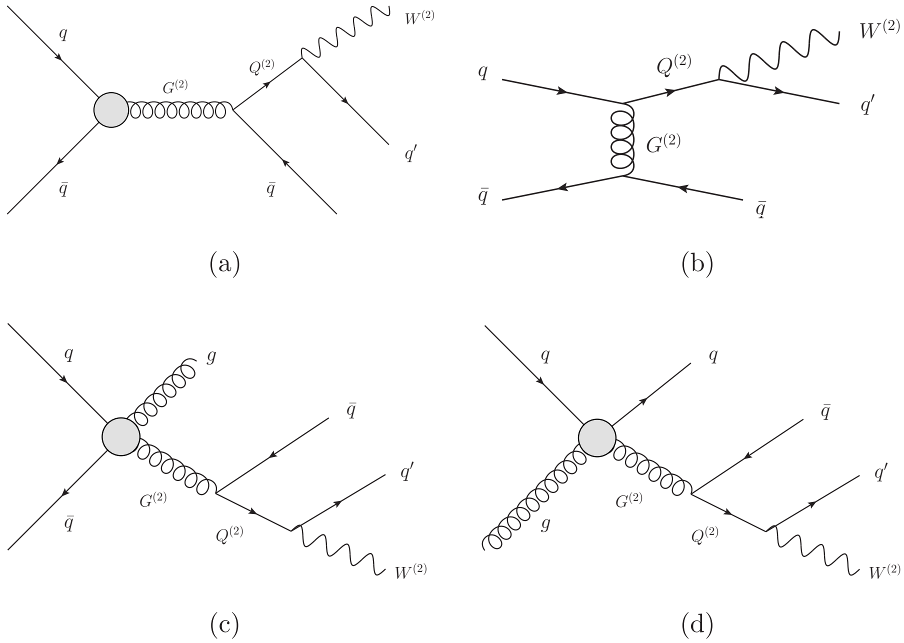

FIG. 3: Feynman diagrams for the production of the $W^{(2)}$ boson.

not possible since the leading vertex g-q-$Q^{(2)}$ vanishes as required by gauge invariance [12]. Figures 3(b)-(d) present associated production of the heavy second KK mode with a SM quark or gluon, $pp \to \bar{q}Q^{(2)},\ gg^{(2)},\ qg^{(2)}$. In order to show the softness of the accompanying SM jet, we present the four-momenta of the heavy second KK mode and the SM particle in the parton c.m frame:

$$k^{\mu}_{(2)} = \left(\sqrt{E^2 + M^2_{(2)}}, E\right), \quad k^{\mu}_{j} = (E, -E)\,, \text{ where } E = \frac{\hat{s} - M^2_{(2)}}{2\sqrt{\hat{s}}}. \tag{6}$$

The steeply falling parton luminosities lead to the production of new heavy particles near the threshold at the LHC: the energy of the accompanying SM particle is quite low.

We summarize the indirect production processes as

$$\begin{aligned}
&pp \to q\bar{q} \to Q^{(2)}\bar{q} \to W^{(2)}q'\bar{q}, \\
&pp \to q\bar{q} \to G^{(2)}g \to Q^{(2)}\bar{q}g \to W^{(2)}q'\bar{q}g, \\
&pp \to gq \to G^{(2)}q \to Q^{(2)}\bar{q}q \to W^{(2)}q'\bar{q}g.
\end{aligned} \tag{7}$$

We impose the condition of the soft SM particles as $1\,\text{GeV} < p^j_T < 30\,\text{GeV}$ at the LHC. Note that the lower cut of 1 GeV is assigned to avoid the infrared and collinear divergences. Since the second KK quarks and gluons are produced through strong interactions, their

production rates are very high and the number of the $W^{(2)}$ boson produced from their decays is considerable.

We also include the sub-leading processes of the $W^{(2)}$ productions associated with a quark or a gluon, *i.e.*, $pp \to q\bar{q} \to W^{(2)}g$ and $pp \to gq \to W^{(2)}q$. At the LHC, the cross section of $pp \to W^{(2)}g$ is much larger than that of $pp \to W^{(2)}q$. The same soft p_T^j cut is applied.

III. IMPLICATIONS ON THE $W^{(2)}$ MASS WITH THE EARLY LHC DATA

The CMS and ATLAS collaborations have reported the results of search for W' boson through the leptonic decay channel. These events are triggered by a single isolated high-p_T lepton and the missing transverse energy of opposite direction and similar in magnitude. The transverse mass of the W' boson for candidate events is calculated as $M_T = \sqrt{2p_T \not{E}_T(1-\cos\phi)}$, where ϕ is the azimuthal opening angle between the lepton and the $\not{E}_T$. From the absence of the signal events in the early LHC data corresponding to an integrated luminosity of 1.1 fb^{-1}, an upper limit at 95% C.L. on the production cross section of W' times the branching ratio of its decay into $\ell\nu$ is set as a function of its mass. The present bounds on the mass of W' is in a reference model with SM couplings: at 95% C.L. the mass bounds are 2.27 TeV (CMS) with 1.03 fb^{-1} electron data and 1.13 fb^{-1} muon data, and 2.23 TeV (ATLAS) with 1.04 fb^{-1} data.

By comparing $\sigma(pp \to W^{(2)}j_{\rm soft}) \times {\rm Br}(W^{(2)} \to \ell\nu)$ with the experimental upper limit, we can determine the lower limit of the $W^{(2)}$ mass, which is shown in Fig. 4 with the reported CMS and ATLAS data. In order to show the importance of the indirect production of $W^{(2)}$, we separately present the events only from the single production and those including indirect production with soft jets. It is clear that the indirect production of $W^{(2)}$ is more important than the signal production of $W^{(2)}$. For example, $M_{W^{(2)}} = 600\,{\rm GeV}$ case has the indirect production of $W^{(2)}$ larger than its single production by a factor of four. Even with enhanced production from the indirect production of $W^{(2)}$, however, the current upper limit is not sufficient to give a significant constraint on the $W^{(2)}$ mass.

We still remain optimistic about the future prospect of the LHC on probing the mUED model through the $W^{(2)} \to \ell\nu$ channel. As can be seen in Fig. 4, the enhancement of the integrated luminosity, from 200 pb^{-1} to 1.1 fb^{-1} at the ATLAS, improves the sensitivity on the upper limit on the W' mass by the factor of almost ten. With the current 5.6 fb^{-1} data,

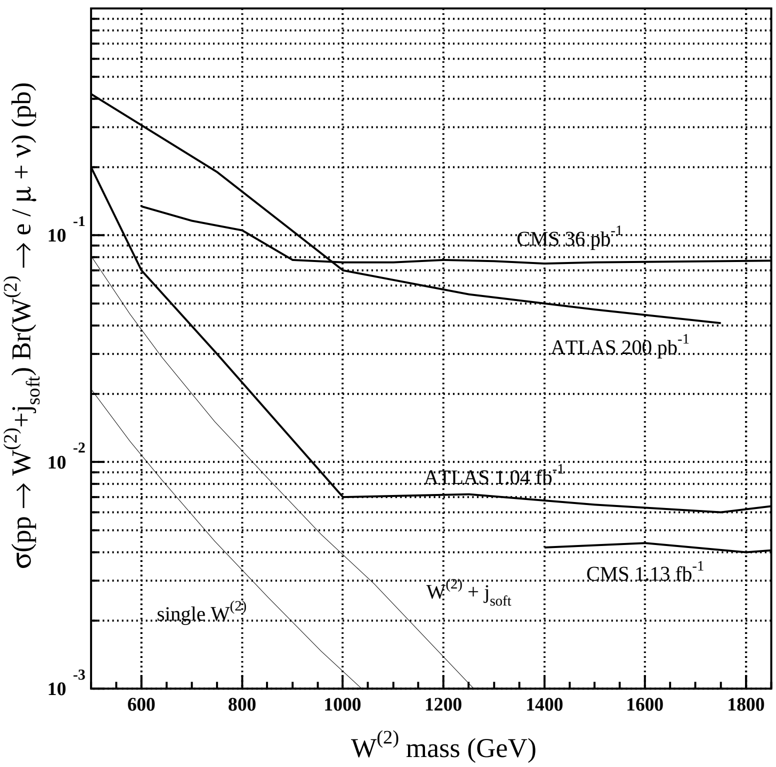

FIG. 4: LHC limits with a counting experiment in the search window $pp \to W' \to e\nu/\mu\nu$ for the $W^{(2)}$ boson in the mUED model.

the ATLAS and CMS are very likely to probe the mUED model for $M_{W^{(2)}} \lesssim 1\,\mathrm{TeV}$. By the end of 2012, we expect at least 10 fb^{-1} data per experiment at the LHC. In the near future, the $W^{(2)} \to \ell\nu$ channel is to cover most parameter space $M_{W^{(2)}} \lesssim 1.2\,\mathrm{TeV}$, which is allowed by the observed relic density. And the inclusion of indirect $W^{(2)}$ production is crucial for the future prospect.

For completeness, we present the Tevatron limit with the data of 5.3 fb^{-1} in Fig. 5. The p_T cut on the accompanying soft jet is $1\,\mathrm{GeV} < p_T < 20\,\mathrm{GeV}$. We find that the Tevatron data cannot give any constraint on the mUED model either. Even with the full data corresponding to an integrated luminosity of 10 fb^{-1}, it is difficult to probe the mUED model through this channel.

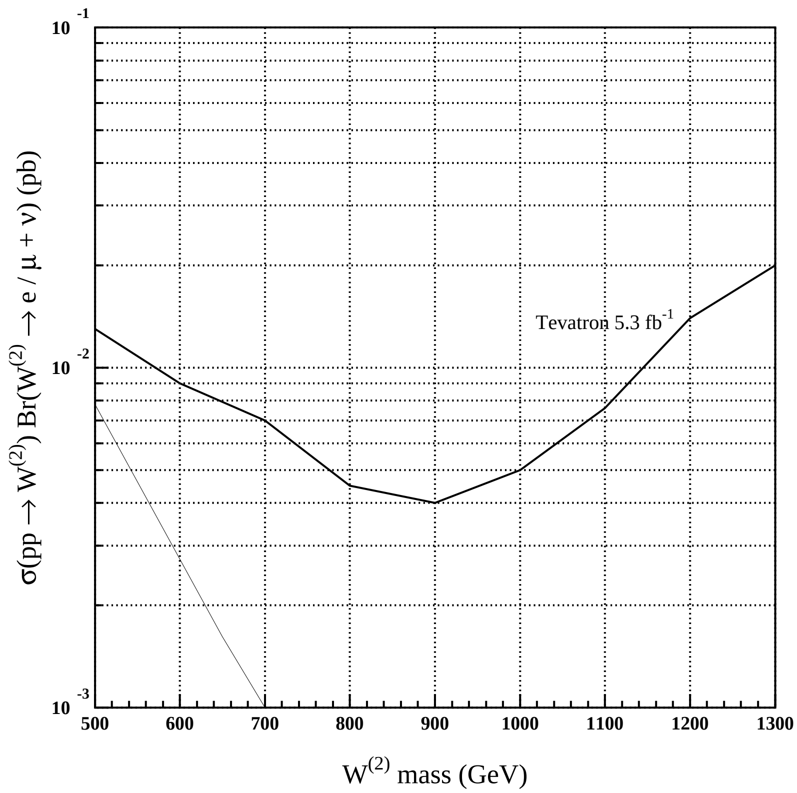

FIG. 5: Limits with the Tevatron data in the search window $pp \to W' \to e\nu/\mu\nu$ for the $W^{(2)}$ boson in the mUED model.

IV. CONCLUDING REMARKS

We have studied the production of the $W^{(2)}$ boson at the LHC to obtain the direct bound on the mUED model. We find that including indirect productions of $W^{(2)}$ boson increases the production cross section by a few times and much improve the sensitivity of the bound on the $W^{(2)}$ mass. The reported LHC analysis based on the data corresponding to an integrated luminosity 1 fb^{-1} is not sufficient to put the direct bound. However, we expect that the currently accumulated data of 5.6 fb^{-1} will yield significant limit on the mUED model. It would be the first direct bound of the mUED model.

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